BBC RD 1979/27

RESEARCH DEPARTMENT REPORT

Synchronization of the Radio – 4(UK) transmitter chain on 200kHz

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Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION December 1979

BBC RD 1979/27
UDC 621.396.61:
621.396.029.51

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Summary

The means by which the carriers of three high-power broadcast transmitters operating at a frequency of 200 kHz are phase locked are described and the effect on the service is assessed.

Issued under the authority of

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION
December 1979
(RA-186)

It uses SI units in accordance with B.S. document
PD 5686.

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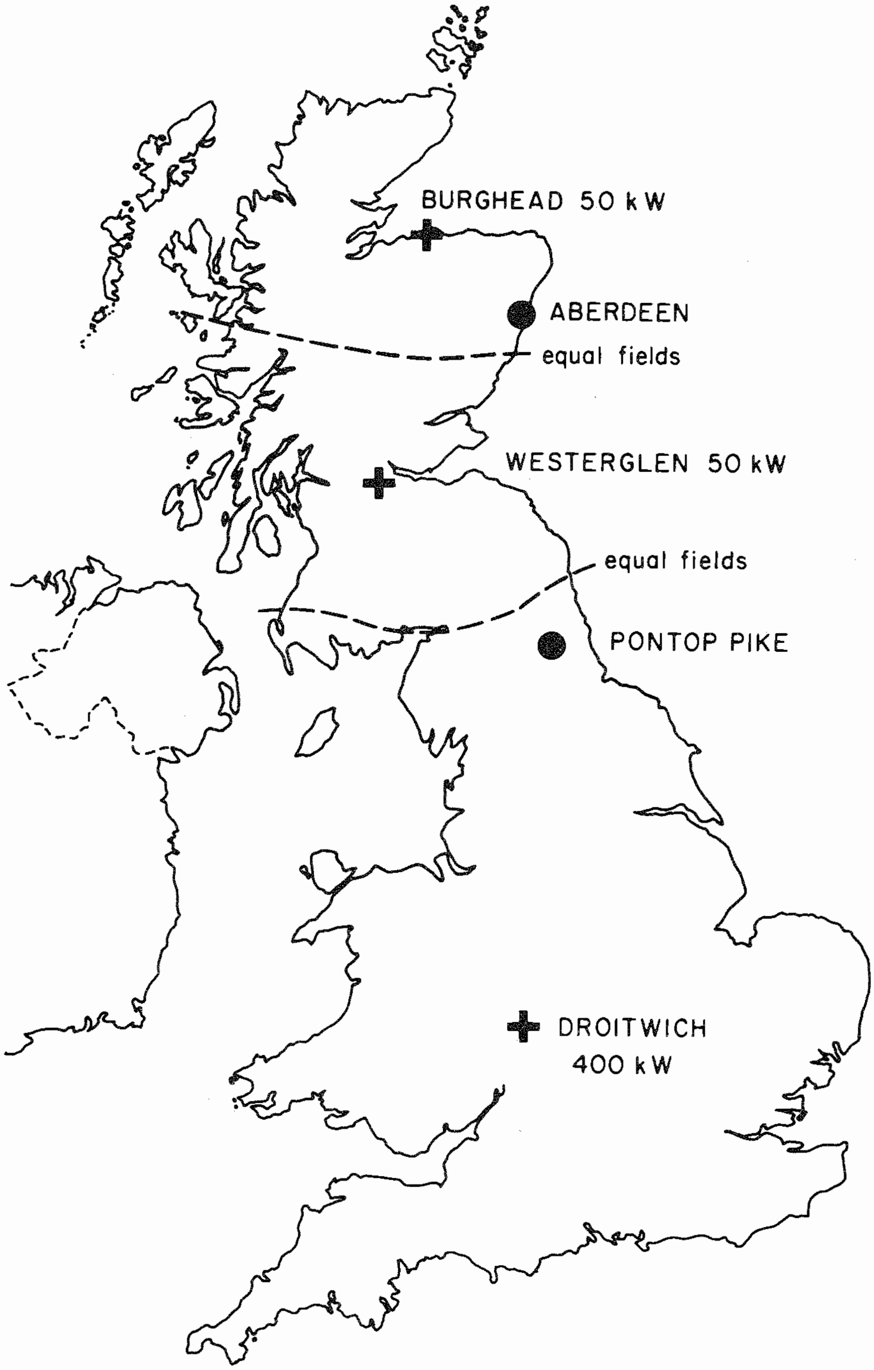

Fig. 1 - Location of transmitters and monitoring sites

+ transmitters • monitoring sites

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1. Introduction

Various changes to the medium frequency (m.f.) transmitters and services in the United Kingdom were introduced on 23rd November, 1978. At the same time the 400 kW low frequency (l.f.) transmitter at Droitwich was to start transmitting a programme – designated Radio-4 (UK) – intended for the whole of the United Kingdom. The Droitwich transmitter did not provide a fully satisfactory service in Scotland so that additional transmitters were needed.

It was the intention originally to serve Central Scotland with 50 kW at a frequency of 227 kHz from Westerglen, near Falkirk, while a second 50 kW transmitter on 200 kHz at Burghead served the Moray Firth area of northern Scotland. This proposal was abandoned when it was realized that the service on 227 kHz would be severely restricted, in daytime as well as at night, by interference from a 2 MW Polish transmitter. Accordingly it was decided to operate both new transmitters on the Droitwich frequency of 200 kHz (Fig. 1). Some additional low-power transmitters operating in the m.f. band were also planned for conurbations such as Newcastle and Aberdeen, which were liable to interference. The development of these proposals and their translation to a viable and efficient service is described in the following sections.

2. Nature of interference between adjacent transmitters

In the region between two transmitters of nominally the same frequency, where the field strengths are comparable, the listener will experience a large amplitude beat at the difference frequency. For transmitters using good quality crystal drives the beat frequency will be typically 0.2 Hz at m.f. and 0.04 Hz at l.f. The listener is made aware of the beat not so much by the variation of signal/noise ratio while the amplitude of the carrier varies but more by the gross non-linear distortion which occurs in the troughs of the beat, i.e. when the two carriers are in antiphase and the sidebands do not cancel at the same time.[1] This distortion may be dramatically reduced by carefully equalizing the modulation delays. Such equalization can only be made correct on one particular line between the transmitters (a locus of constant difference in propagation delay) and it is reasonable to try to make this line coincident with the line of equal field strengths. However, the two lines are governed by different laws so that the coincidence cannot be exact.

3. Use of Droitwich as frequency standard

Since the earliest days of broadcasting in the United Kingdom great care has been taken to maintain a high frequency stability for the transmitters. At the present time the Droitwich 200 kHz transmitter drive frequency is derived from a rubidium vapour standard supplied by the National Physical Laboratory. This is regularly checked against the caesium frequency standard of the NPL and the results are published. It is understood that considerable use is made of Droitwich as a frequency standard and so it would have been unfortunate if the facility were to be removed from some parts of the country, by the addition of less stable transmitters. One proposal was made that the new transmitters should be given a small frequency offset relative to that of Droitwich so that their presence could be detected. This would still require as great a frequency stability at Westerglen and Burghead as at Droitwich and it was thought better to use the same frequency throughout. Rubidium vapour frequency standards have, therefore, been installed at both Westerglen and Burghhead. If no further measures had been taken, the three transmitter frequencies would have drifted slowly relative to each other. In the same way, the standing-wave pattern between two adjacent transmitters would also have drifted slowly. This would have caused annoyance to those listeners in areas of high standing-wave ratio. An installation which was satisfactory one week would become unsatisfactory the next, with periods of distortion lasting 24 hours. The three transmitters have, therefore, been phase locked to give stable listening conditions.

4. The phase-locking system

In order to phase lock two transmitters it must be possible to compare their frequencies either

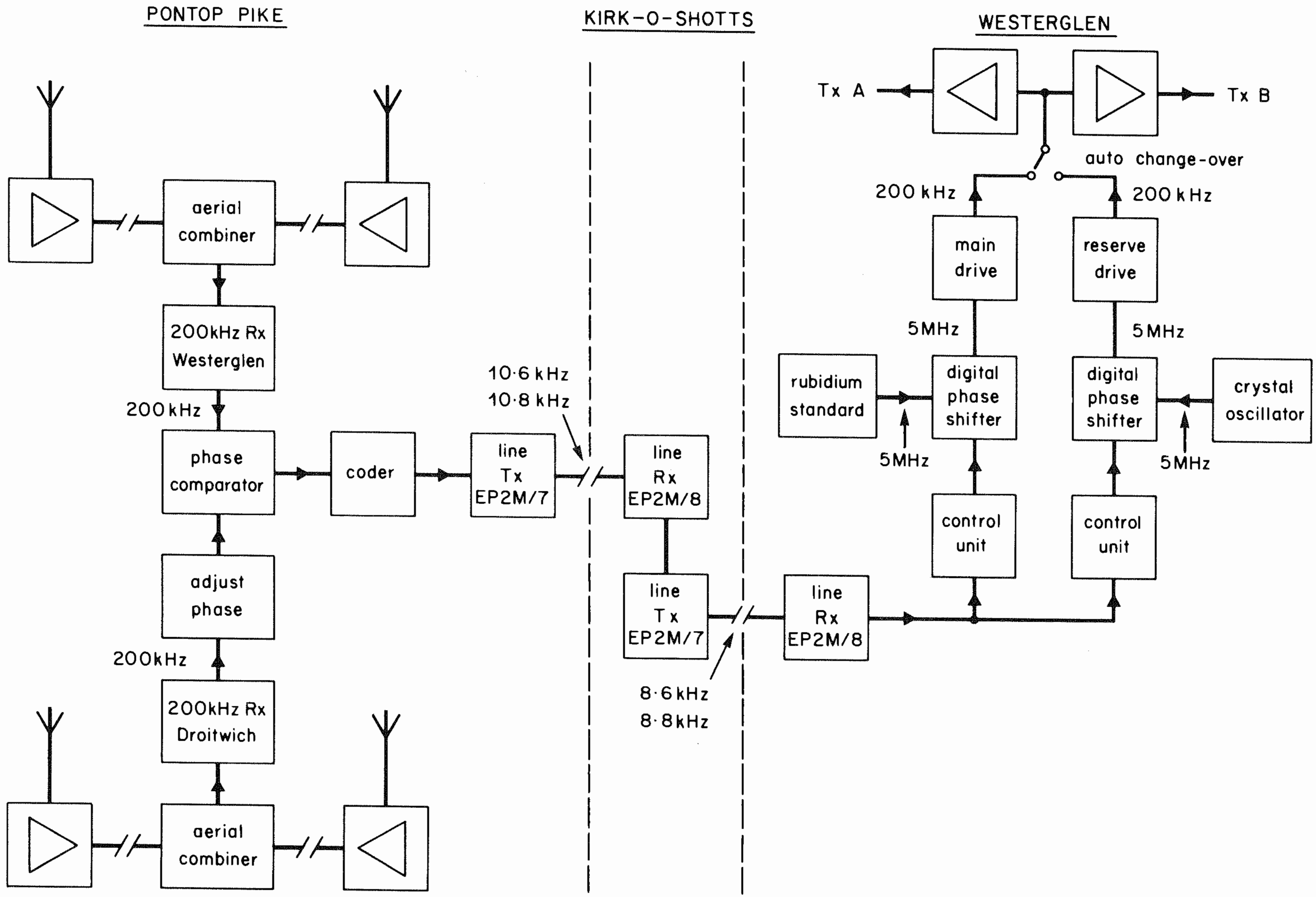

Fig. 2 - The Droitwich–Westerglen control system

directly or through the use of a common reference. The latter approach was considered, using either external low-frequency transmissions, such as Rugby MSF on 60 kHz, or internally available signals, such as the master clock frequency used in pulse-code-modulation links, but seemed likely to require more complex equipment and to be inoperative more often. Accordingly, sites were chosen at which a direct comparison of signals from adjacent transmitters could be made. Ideally, these sites should have had equal fields from the two transmitters. However, it was also necessary to find sites with existing lines or links that could be used for signalling data to one of the transmitters, and this restricted the freedom of choice. The sites finally selected were Pontop Pike and Aberdeen (Fig. 1). These are used, respectively, to lock Westerglen to Droitwich, and Burghead to Westerglen. Directional aerials are used to sample each transmission independently of the other (at least in theory) and the phases are compared. Any difference in phase from the norm results in a control signal being sent to the 'slave' transmitter. This signal is coded onto tones at frequencies just above the audio-frequency band and carried by line to the transmitter. After decoding, the control signal effects a phase shift in the 5 MHz reference frequency of the rubidium standard. Fig. 2 shows the schematic arrangement for the Droitwich–Westerglen pair. That for the Westerglen–Burghead pair is similar.

For instrumental reasons to be discussed later it was decided that the phase would normally be controlled in steps of 1.3° but that a larger step (21°) would be available if required to ensure rapid locking. After initiation of a step, a period of up to 4 seconds is required for the system to settle. Since two control loops were being operated in tandem the minimum interval between steps becomes 8 seconds. Thus the maximum frequency change that can be corrected with small phase steps is 4.5×10^{-4} Hz. With all large phase steps the corresponding figure is 7.3×10^{-3} Hz.

There are three principle sources of phase variation to be controlled:

(i) diurnal variations caused by temperature variations of the drive,
(ii) long-term drift or ageing of the drive,
(iii) propagation variation in the paths between transmitters and monitoring points.

Each type of variation must be considered in detail in order to estimate the performance of the control system.

The rubidium drives have a frequency stability of less than 2×10^{-10} for a temperature variation from −10°C to +50°C. At 200 kHz this corresponds to a frequency change of less than 4×10^{-5} Hz which is well within the capability of the control system on small steps. In practice the rubidium drives will not be subjected to such extreme temperature variations. Moreover, each transmitter will be subject to similar diurnal temperature variations so that frequency differences from this cause are likely to be very small indeed.

The long-term frequency stability of the rubidium drives corresponds to a fractional change of less than 3×10^{-11}/month. Assuming the two transmitters being compared start off with the same frequency but drift in opposite directions, the relative stability is 1.2×10^{-5} Hz/month. If the drifts were to continue in the same direction and at the same rate, the control would be fully occupied with single step corrections after a little over 3 years. The frequency of the drive would then need to be reset using the manual frequency trim provided; this has a range of 1×10^{-9} or 2×10^{-4} Hz at 200 kHz. This performance may be compared with that of the reserve drives which are crystal controlled. The crystals have an initial ageing rate of not more than 1×10^{-8} per day corresponding to a frequency change at 200 kHz of 2×10^{-3} Hz/day. Thus, if the crystals were correctly trimmed to begin with, the control system would reach saturation on small phase steps after 5.4 hours and on large phase steps after 3.6 days. Thus, it is not practical to control crystal drives with the present system. A reserve rubidium standard is held in store for use either at Westerglen or Burghead.

The sensing equipment at the monitoring points will see relative phase changes resulting from sky-wave propagation. Suppose the effective height of reflection of sky-wave from the ionosphere is 80 km during the day and 90 km at night. If the distance between transmitter and monitor is 325 km then the sky-wave path length changes by 6 wavelengths in a period of perhaps 6 hours. This is equivalent to a Doppler frequency change of 2.8×10^{-4} Hz which is within the capability of the control system. Most of the time the ground wave at the monitoring site will predominate and the frequency changes will be less than the above. At times, however, when ground and sky-waves are nearly equal and anti-phased (i.e. when the signal suffers a fade) more rapid phase changes will occur. It may be shown

from the above assumptions that the maximum fading range that the system can cope with is 35 dB. It is found from observation that fading ranges are normally much less than this so that the system should be capable of dealing with the imposed phase modulation for a very large percentage of the time.

5. The Pontop Pike monitoring site

It was pointed out in the previous section that a number of considerations influenced the choice of monitoring sites and inevitably compromises had to be made. For Pontop Pike the biggest disadvantage is that the site is 40 km south of the predicted line of equal field strengths from Droitwich and Westerglen. As a result the field of Droitwich at Pontop Pike was expected to be 6 dB greater than that of Westerglen (see Table 1).

In the event Westerglen was obliged to operate at half power for the first three months of operation so that the disparity at Pontop Pike was increased to 9 dB. This increased the reliance on the directivity of the monitoring aerials. The design of these may now be considered.

5.1. The monitoring aerials

The aerials are a vital part of the installation in as much as they are required to select one of the transmissions and to give a high discrimination against the rest. At the same time the wavelength is such that a large site would be required for the usual type of directional aerial.

Consider the elementary case of only two transmissions laying down equal fields at the monitoring site and assume that each aerial has a discrimination against the unwanted signal of 20 dB. It is shown in the Appendices that when the system is near balance, so that the phase difference between the two signals is small, the measured phase difference is almost 20% less than the actual phase difference. Any inequality of the fields at the monitoring site will increase the errors as will a third nearly-synchronous signal.

The simplest type of directional aerial is the loop or its ferrite equivalent. Such aerials can give good results in day time provided that they are not subject to pick-up of the E-component of the field. At night-time they are less satisfactory. A null set up on the ground wave does not hold for the horizontally-polarized component of electric field of the sky-wave.[2,3] This was important since measurements of Droitwich at Newcastle had shown that the amplitude of sky-wave could exceed that of the ground wave.[4] The simple loop was, therefore, not the preferred choice of directional aerial.

The use of a vertical whip aerial overcomes the night-time difficulty and two may be spaced to give a directional system. Directional horizontal radiation patterns ranging from figure-of-eight to cardioidal shapes may be readily obtained. It was desirable to use a whip aerial fitted with an active element in order to make incidental pick-up on the rather long connecting cables negligible in comparison with the wanted signal. Fortunately, a design of a suitable linear amplifier

TABLE 1

Estimated Field Strengths at Pontop Pike, dB rel. 1μV/m

Transmitter	Distance	Ground Wave	Night-time Sky-Wave Median
Droitwich	287 km	+78 dB*	+75 dB
Westerglen	178 km	+72 dB	+68 dB
Burghead	332 km	+64 dB	+65 dB
Leningrad	1961 km	–	+49 dB
Moscow	2426 km	–	+43 dB
Warsaw	1523 km	35 dB	+45 dB**

* measured value
** winter day-time

was available.[5] The length of the whip was increased to 3.6 m and the input was tuned to 200 kHz to increase the immunity to strong local transmissions. Provision was also made for supplying the power for the amplifier along the co-axial cable.

Directional horizontal radiation patterns (h.r.p.) can be obtained with relatively closely-spaced aerials but the phasing becomes very critical and the resultant signal is much less than that from either aerial alone. Fig. 3 shows, for cardioid and figure-of-eight radiation patterns, how the combined output of two aerials relative to a single aerial depends on the spacing between them. In the interest of deep and stable nulls it is desirable that the combined output should be comparable to that of the single aerial. The spacing between aerials should, therefore, be in the range 100 m to 250 m, depending on the h.r.p. The pattern used for the reception of Droitwich at Pontop Pike is shown in Fig. 4; it has two nulls with an angular separation of 28° corresponding to the difference in the directions of Westerglen and Burghead. In the direction of

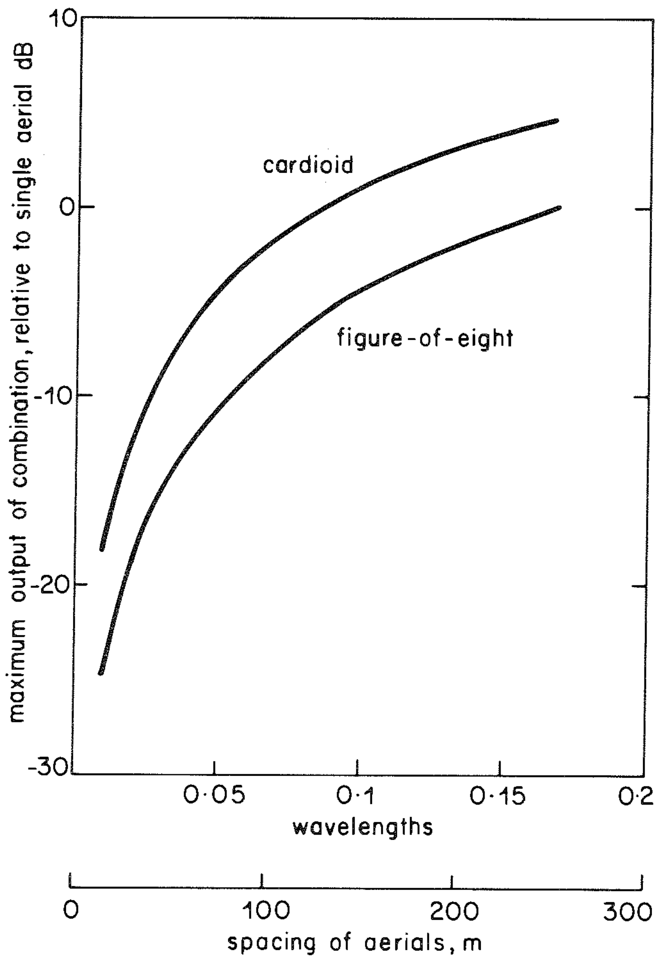

Fig. 3 - The relative output of closely-spaced aerials

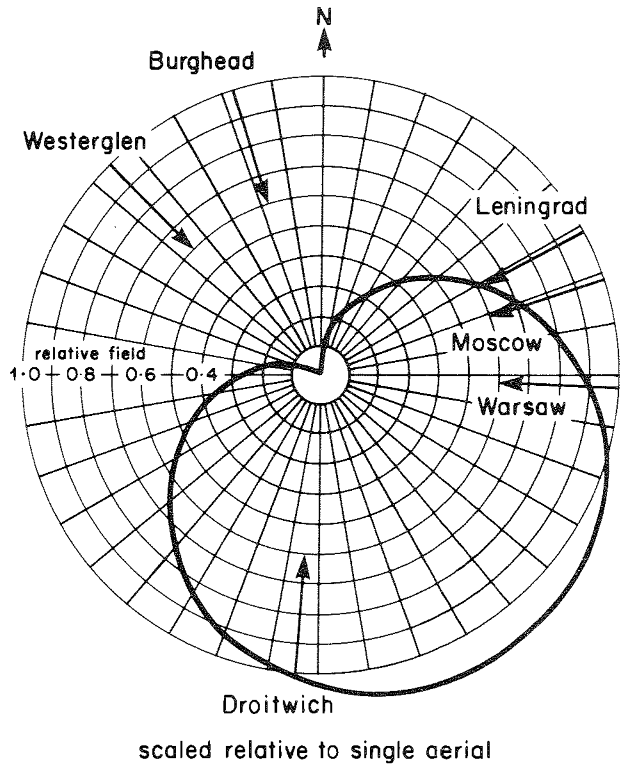

Fig. 4 - Horizontal radiation pattern of aerial pair receiving Droitwich at Pontop Pike

Droitwich the aerial response is less than 1 dB below the maximum and is almost exactly the same as that from a single aerial. The aerial pair used for the reception of Westerglen poses a much greater problem. It would be perfectly feasible to provide an arrangement having nulls on Droitwich and Burghead but this would lead to a large lobe to the east and a small lobe to the west, with reception of Westerglen being taken off the side of the latter. Now the frequency allocation of 200 kHz is shared by stations at Leningrad, Moscow and Warsaw, which are all to the east. It was considered preferable to use the arrangement shown in Fig. 5 where the two aerials are antiphased to give a figure-of-eight h.r.p. The null is placed on Droitwich, which is by far the strongest signal in the locality. Burghhead is attenuated by some 6 dB relative to Westerglen. Since the incident ground-wave field from Burghead is expected to be 8 dB below that of Westerglen (Table 1), the Burghead signal at the receiver will be only 14 dB less than it. This is rather high but the only alternative would seem to be the use of a superdirective array.

The disposition of the whip aerials on the site at Pontop Pike is shown in Fig. 6.

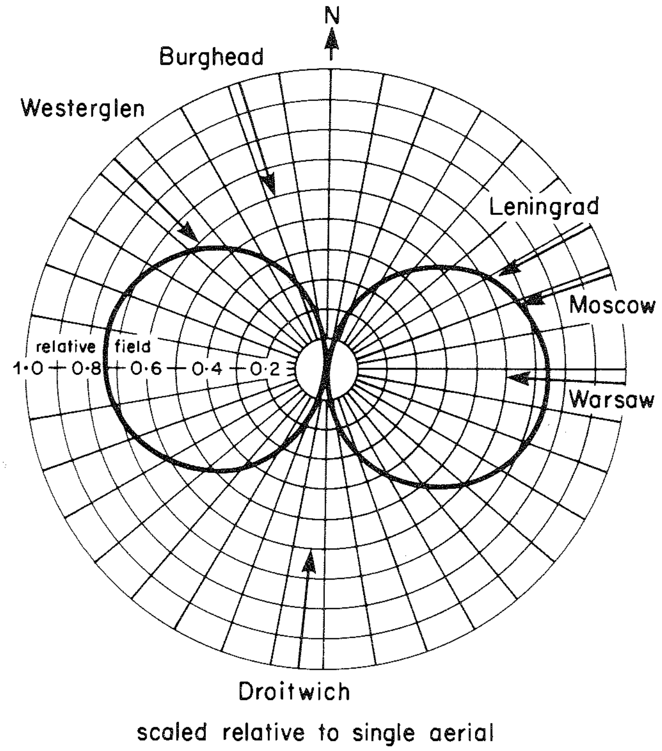

Fig. 5 - Horizontal radiation pattern of aerial pair receiving Westerglen at Pontop Pike

5.2. Aerial combining units

The aerial combining units are required to modify the amplitude and phase of the signals received from the monopole aerial pairs, so that the radiation pattern nulls can be arranged in the desired directions as mentioned above. To achieve this, control over the amplitude and phase of the contribution of at least one of the aerial feeds is required before combination. In the units used at Pontop Pike, each channel is provided with independent controls for both amplitude and phase shift. Each combining unit comprises two variable-gain-input differential amplifiers, each fed from one of the output feeders from the pair of monopoles to be controlled. The output loads of the differential amplifiers are either an inductance-potentiometer or capacitor-potentiometer combination to give adjustable phase retardation in the range 0° to −90° or phase advance of 0° to 90°. These outputs are fed through high-impedance-input f.e.t. amplifiers and combined in a unity-gain summing amplifier.

The phase adjustment range given by the above arrangement is 180° only, but a full 360° phase range can be obtained by interchanging the

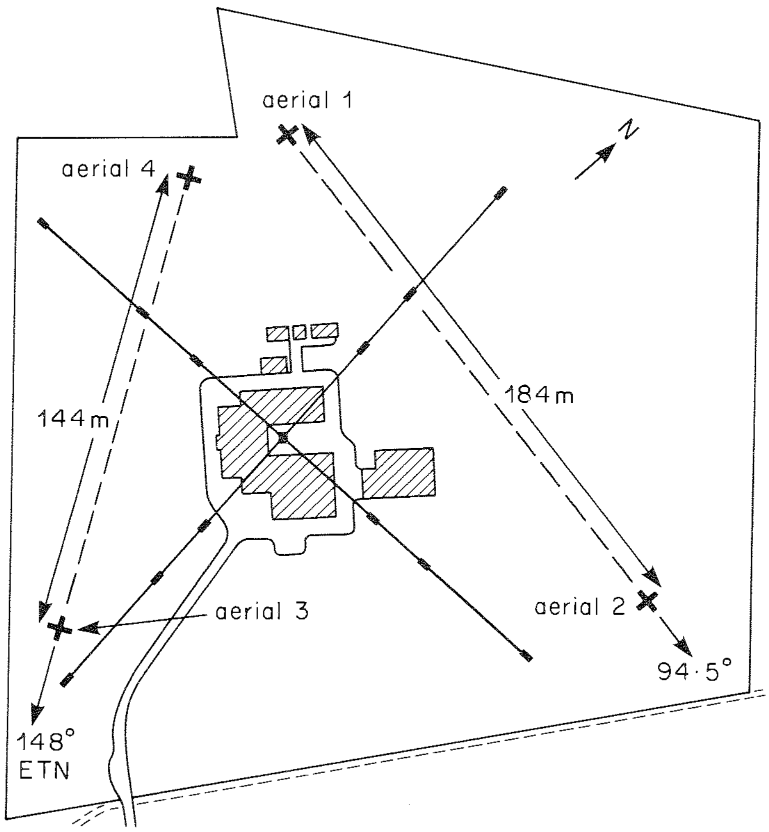

Fig. 6 - Disposition of whip aerials at Pontop Pike

input connections to the unit. An advantage of restricting the phase-shift adjustment range of each channel to 90° is improvement in phase stability.

At the present time, nulling out of an unwanted signal must be performed when that signal alone is present and can only be achieved during night-time periods, when normal programme transmission has ended. Null depths of −35 dB have been achieved with these units, although some difficulty has been experienced at the monitoring sites with interfering signals blurring the nulls during the evenings and night-time.

The combining units also insert a 38 V supply on the aerial input connector in order to power the aerial amplifiers.

5.3. 200 kHz receiver

The function of the monitoring equipment is the measurement of relative phase between the two transmissions which are to be phase locked. It is essential, therefore, that the receivers are able to retrieve the carrier from the incoming amplitude-modulated signals. Removal of the modulation from the signals is not possible with conventional lumped-circuit filters, although a substantial reduction in sideband level can be achieved using a narrow band crystal filter. An alternative way is to use a phase-locked-loop circuit with a long time constant, so that not only is the amplitude modulation removed but also any incidental phase modulation arising in the transmitter circuits.

The receivers have been specially built for the monitoring equipment and are intended solely for reception of 200 kHz signals. They are a.g.c. controlled selective amplifiers followed by phase-locked-loop circuits. A block schematic diagram of a receiver is shown in Fig. 7. The r.f. signal is fed through a 40 dB feedback amplifier to a 7 kHz wide band-pass filter centred on 200 kHz and to an electronic attenuator. Additional amplifiers give 70 dB of gain and are followed by a signal detection circuit. The detector output is fed to a 5 Hz active low-pass filter which drives both a signal strength meter and the gain control terminal of the electronic attenuator. The detector also provides, after filtering, an audio output for monitoring purposes.

The automatic gain control provides an almost constant r.f. output of 3 V peak over an input signal range of 100 μV to 20 mV, with less than 10° of phase change between these extremes. The output of the last stage of r.f. amplification over-drives an open-loop integrated-circuit amplifier to provide a sine-to-square wave conversion. This process removes a substantial portion of the amplitude modulation. The converted square wave is fed to the phase-comparator section of a phase-locked-loop integrated circuit.

A voltage controlled 2 MHz crystal oscillator is phase locked to the incoming reference signal. Its output is divided by ten and the resultant 200 kHz applied to the second input of the comparator section of the phase-locked-loop integrated circuit. The comparator output drives an integrator which provides the bias for the varactor diodes controlling the frequency of the crystal oscillator. The divided output of the oscillator, after bandpass filtering, is the output of the receiver. In-lock and out-of-lock detectors determine when the receiver is phase-locked to the

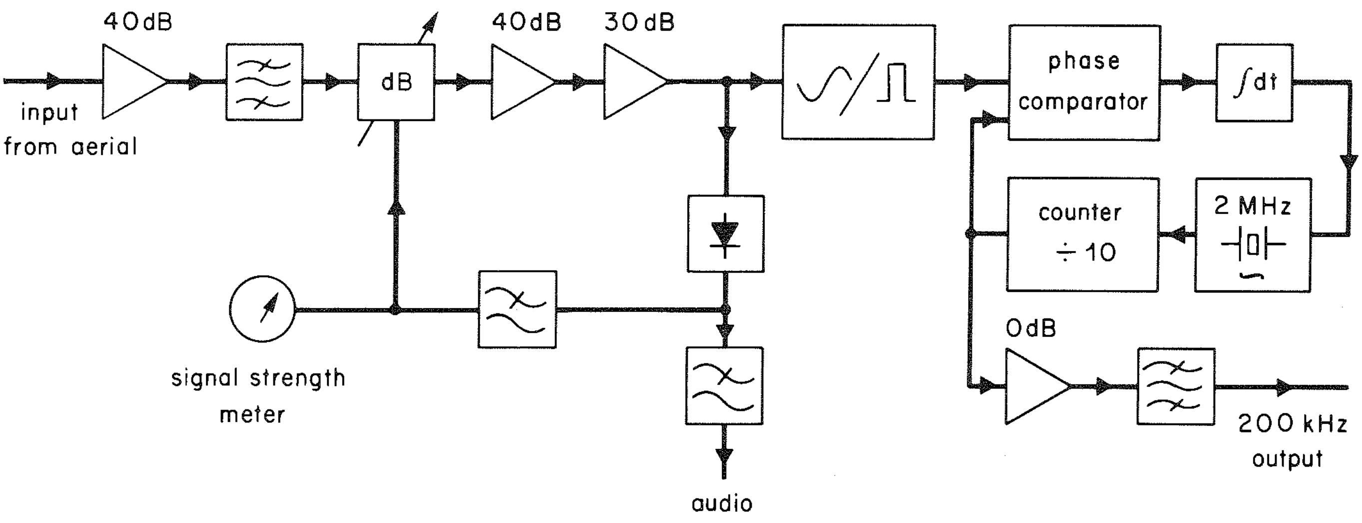

Fig. 7 - Schematic of 200 kHz receiver

incoming signal. This is indicated by a LED display on the receiver front panel. The phase-lock information is also supplied as an executive control to the signal coder unit so that no phasing instructions are sent if either receiver is out of lock. (See Section 5.6.)

5.4. The phase adjuster

The 200 kHz phase adjuster is used to preset the phase between the fields arriving from the reference and phase-controlled transmitted signals. It also provides the facility for phase correction when replacement units are installed at the monitoring site (for instance, the receivers produce an arbitrary phase shift due to slightly different tuning of filter circuits and variations due to component tolerances). The phase adjuster is part analogue and part digital in operation. The analogue section provides a continuous phase setting of ±5°, whereas the digital section provides integral 10° phase steps from 0 to 350°. The phase setting is by way of a preset potentiometer and thumbwheel switches mounted on the front panel of the unit. A schematic diagram of the unit is shown in Fig. 8. The analogue section comprises fixed phase-shift networks in addition to the adjustable phase-shift network; the former corrects for the phase shift through the unit when the phase setting is zero. The analogue section is followed by a sine-to-square-wave converter.

The digital section consists of a 7.2 MHz oscillator phase locked to the incoming 200 kHz square wave from the sine-to-square-wave converter. Since the frequency ratio between the phase-locked oscillator output and the incoming 200 kHz waveform is 36:1, a reference point on the 7.2 MHz waveform (say the positive going edges) occurs at 10° intervals of the 200 kHz waveform. The phase setting is performed by counting a predetermined number of transitions of the 7.2 MHz waveform from a common point on the incoming 200 kHz signal before initiating the start of a divide-by-thirty-six counter, each count representing a phase lag of 10°. Determination of the number of transitions counted is provided by the binary-coded decimal (BCD) thumbwheel switches; this is converted to a nines complement code by a programmable-read-only-memory (PROM) and provides the preset instruction for BCD counter A. The 200 kHz and 7.2 MHz signals are applied to a pulse synchronizer. This gives an output pulse when the rising edges of the two waveforms are coincident, and provides a reset pulse for the counters. This pulse cannot be applied directly to counter A without incurring a double count corresponding to a 20° phase error in the output waveform. The error occurs because the counters are synchronous and there is a one clock period delay between an instruction to load or reset and its operation. To overcome this, a divide-by-thirty-four counter is used between the pulse synchroniser and the BCD counter A; this ensures that the counter A is loaded two pulses before the start pulse occurs. On completion of the preset count on counter A, the divide-by-thirty-six counter B is reset. The output of this counter is a 200 kHz waveform delayed by the desired phase shift relative to the incoming 200

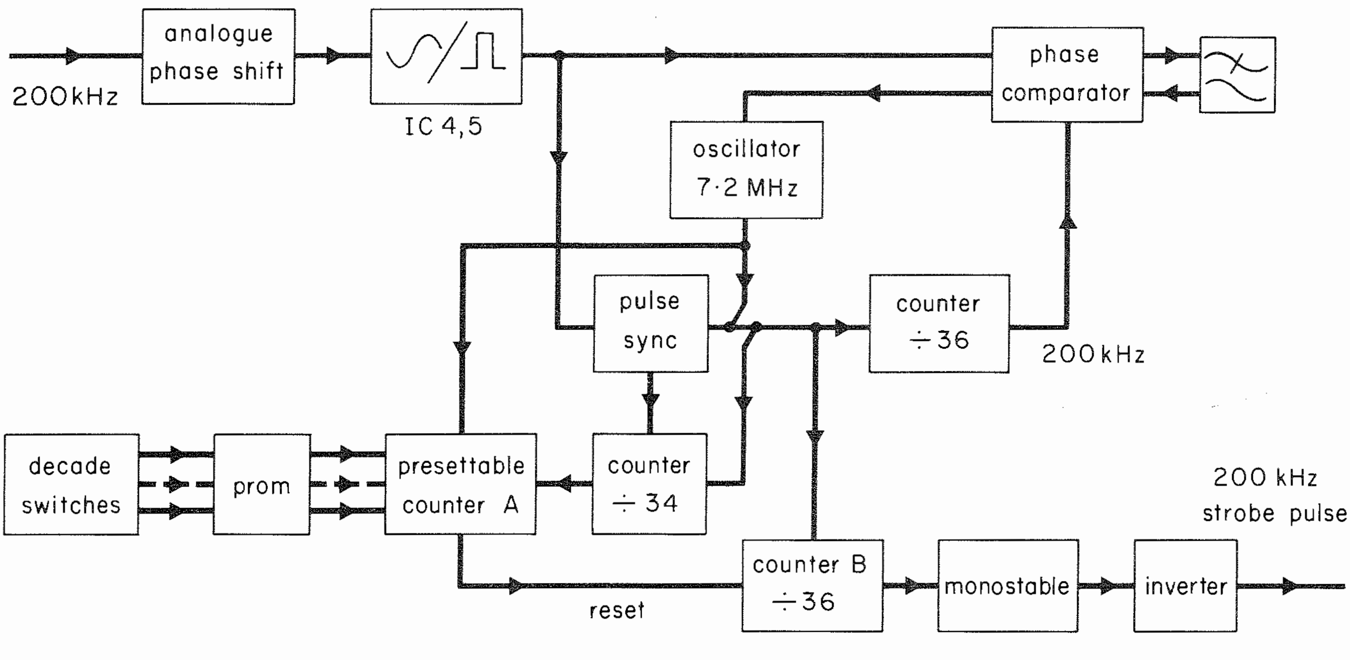

Fig. 8 - 200 kHz digital phase adjuster

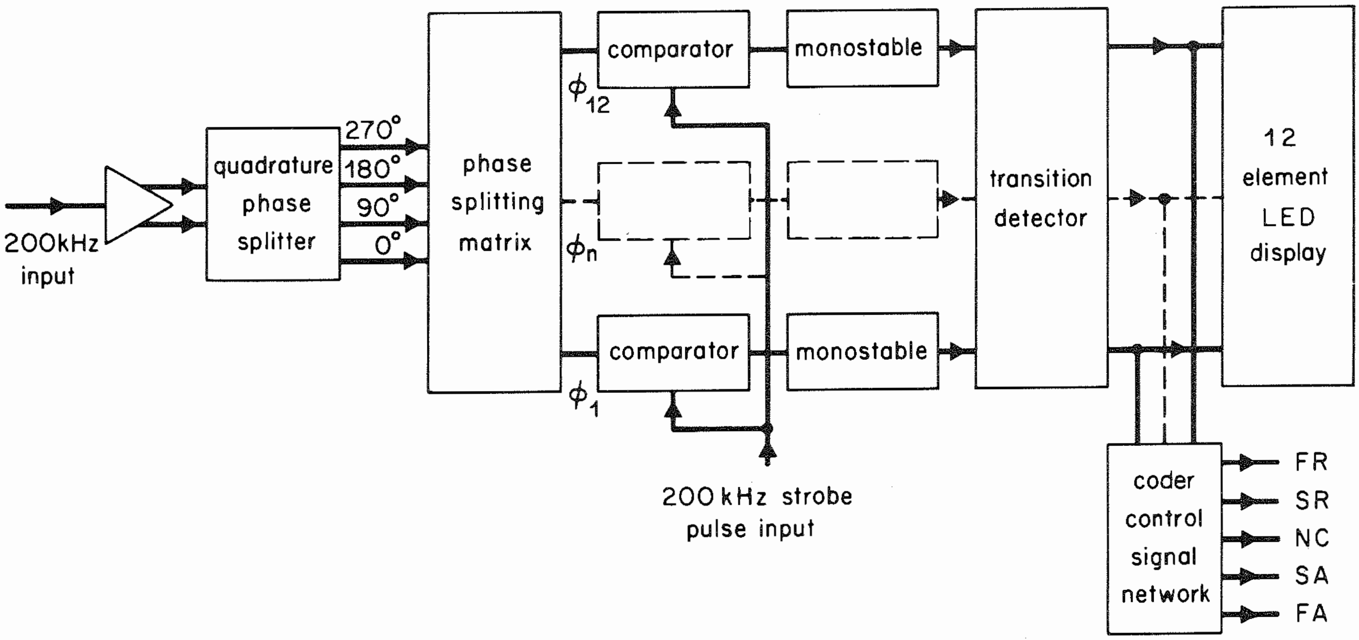

Fig. 9 - 200 kHz phase comparator

kHz signal. The final processing is through a monostable and inverter, and provides a 40 ns wide 200 kHz pulse output.

5.5. The phase comparator

The phase comparator, used to determine the relative phase of the applied input signals, gives a visual display of the relative phase angle and passes phase data to the signal coder unit.

The comparator (Fig. 9) has two inputs via type BNC sockets on the front panel of the unit, one fed directly in the Pontop Pike equipment, from the Westerglen receiver and the other fed with the 40 ns wide 200 kHz pulses derived from Droitwich in the phase adjuster unit. The input stage, a long-tail-pair transistor amplifier, is fed directly from the Westerglen receiver. Its differential outputs are directly coupled to two transistor emitter-follower stages giving antiphase signals across their emitter loads. These signals are applied to a phase-splitting network to give quadrature phase components. The four-phase voltages are applied to a phase splitting network which drives the inputs of twelve comparator integrated circuits in phase rotation.

The phase increments between comparators are in 40° steps except for $\phi_2 - \phi_1$, $\phi_3 - \phi_2$ and $\phi_1 - \phi_{12}$ which are 10°, 6° and 10° increments respectively. The comparators are dual-input-pair comparators with strobe. When the strobe input is high the comparator operation is normal, but when it is low the output is inhibited.

At any instant during the applied 200 kHz cycle, the potential applied to the inputs of a group of approximately half of the comparators will be positive and above their threshold level. Application of the strobe pulse will allow the outputs of these comparators to rise to a logical 1 state for a period corresponding to the strobe pulse duration of approximately 40 ns.

The output pulses from the comparators drive edge-triggered monostables and if the signal and strobe inputs remain in the same relative time phases, the same group of monostables are repeatedly retriggered with their outputs held high.

The transition detector comprises a series of gates connected between monostables adjacent in the phase sequence. It is used to detect one of the two transitions between the groups of high and low output states. This causes a change of state on one of the output lines and is indicated by the appropriate LED in the front panel display. This information is also passed on to the coder signal logic which produces the output code shown in Table 2 on its five output lines.

When the indicated phase is 0°, the relative input phase is within the range 0° ± 3° and a 'no change' is ultimately signalled to the transmitter. The 10° phase indicators show the phase increment beyond the 0° window; +10° covers the input phase range from +3° to +13° while −10° covers the phase range from −3° to −13°. When the input phase is within one or the other

TABLE 2

Output code of phase comparator

Phase indicated	FA	SA	NC	SR	FR
$> +10^\circ$	0	1	1	1	1
$+10^\circ$	0	0	1	1	1
0°	0	1	0	1	1
-10°	1	1	1	0	0
$< -10^\circ$	1	1	1	1	0

of the two ranges either an advance or a retard signal, as appropriate, is sent to the transmitter unit and small phase step changes of 1.3° are made. When the phase indications are greater than +10° or less than −10° the instructions sent to the transmitter are for a fast advance or retard and large phase step adjustments of 21° are made.

5.6. Signal-coder unit

The signal-coder unit translates the signals from the phase comparator board to the appropriate code for driving the line signalling equipment. The unit has a five LED display; these indicate the phase change required at the transmitter, whether it should be advanced or retarded with a fast change (21° step) or a small change (1.3° step) or no change. The unit is also controlled by the phase-lock condition of the receivers, i.e. if one or both receivers are unlocked, the freeze light will glow and a no-change signal will be sent to the transmitter unit. A manual control switch, mounted on the front panel, performs the same function.

Satisfactory operation of the line signalling equipment requires that at least one of its two input lines is maintained at a logical 1 (two logical zeroes are interpreted as a line failure and result in an alarm at the receiver). There are, therefore, only three states possible to meet these requirements, these are (1,1), (1,0) or (0,1). This does not permit sufficient data to be sent to the transmitter phase controller. By allowing one input to oscillate between logical 0 and 1 at a 2.5 Hz rate, while the other input is held at logical 1, the input requirement is not invalidated and two further control states are provided.

Table 3 gives the input and output states for the unit.

TABLE 3

Output code of signal-coder unit

	Line 1	Line 2
Advance	0	1
Fast Advance	⎍	1
No change	1	1
Retard	1	0
Fast Retard	1	⎍
Freeze	1	1
Rx unlock	1	1

6. The Aberdeen monitoring site

The choice of Aberdeen as a monitoring site was largely a matter of expediency. The more obvious site was that of Redmoss, 4 km to the south, but this was in process of being refurbished and was unsuitable at the time for the installation of experimental equipment.

6.1. The monitoring aerials

The only area available for aerials at Beechgrove House, Aberdeen, was a small flat roof and this dictated the use of ferrites. A standard BBC design was available (UNI/163) which had an amplifier built in. The aerial was not screened against pick-up of the electric field and so there was some blurring of the nulls (a screened version is being prepared). Figs. 10 and 11 show how the h.r.p.s of the ferrites were set relative to the wanted and unwanted signals. This arrangement gives relatively little discrimination against Droitwich. It may be seen from Table 4 that the ground-wave signal strength of Droitwich at Aberdeen is only 9 dB below that of Westerglen. Taking into account the aerial directivity, it is shown in Appendix II that there may be a constant error in the measurement of phase angle between the Westerglen and Burghead signals of up to 9 degrees. At night time the position is worse with a comparable contribution from the sky wave. For this reason a more sophisticated aerial system is under consideration.

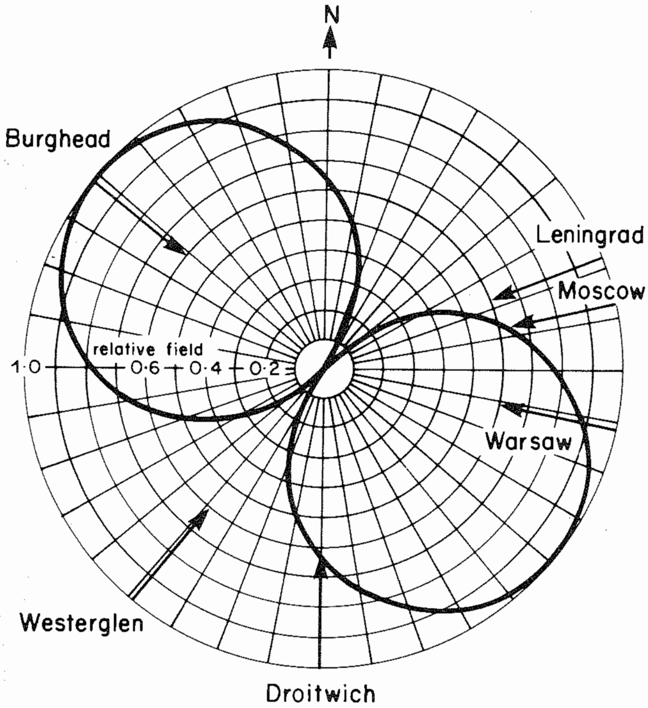

Fig. 10 - Horizontal radiation pattern of ferrite aerial receiving Burghead at Aberdeen

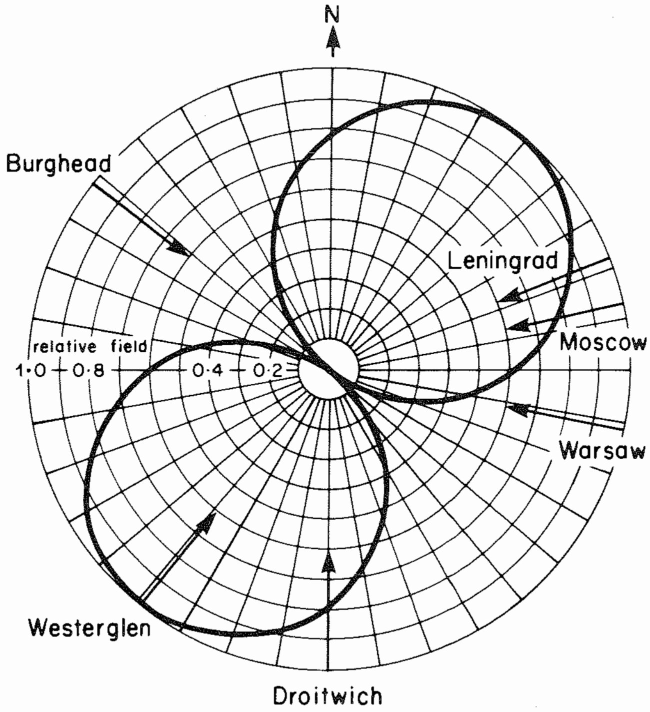

Fig. 11 - Horizontal radiation pattern of ferrite aerial receiving Westerglen at Aberdeen

6.2. Aberdeen monitoring equipment

The equipment used at the Aberdeen monitoring site is essentially the same as that used at Pontop Pike. There are, however, minor differences owing to the use of ferrite aerials instead of monopoles. The aerial combining units and the associated 38 V power supply used for the monopoles are replaced by aerial insertion units which inject a 10 V d.c. power supply on to the ferrite aerial output feeders.

7. Line signalling equipment

BBC Designs Department line signalling equipments EP2M/7 and EP2M/8 are used. In its standard form this equipment allows only three states

TABLE 4

Estimated Field Strengths at Aberdeen, dB rel. 1 μV/m

Transmitter	Distance km	Ground Wave	Night-time Sky-Wave (Median)
Westerglen	166	78 dB	69 dB
Burghead	101	81 dB	69 dB
Droitwich	540	69 dB *	70 dB
Leningrad	1871	–	49 dB
Moscow	2377	–	43 dB
Warsaw	1575	–	45 dB **

* measured
** winter daytime

to be sent. The equipments were, therefore, modified to send and detect two additional states as detailed in Table 3 above. The equipments signal with a pair of high audio frequencies and are provided with filters so that the line may be used simultaneously for a conventional audio circuit.

The link from Pontop Pike to Westerglen has to be made in two stages. From Pontop Pike to Kirk-O'Shotts an audio line is used which carries reserve BBC-1 and BBC-2 television sound feeds multiplexed onto the one circuit in 5 kHz frequency bands; the signalling is performed with tones of 10.6 kHz and 10.8 kHz. From Kirk-O'Shotts to Westerglen the line carrying the Radio-4 (UK) programme feed is used. This line has a poorer high-frequency response and lower-frequency tones of 8.6 kHz and 8.8 kHz have to be used. Thus it is necessary to have a pair of line signalling equipments at Kirk-O'Shotts in order to effect the signalling tone frequency change.

The link from Aberdeen to Burghead is by way of Meldrum on a line carrying Radio-4 (UK) programme feed. The signalling tones in use are 8.6 kHz and 8.8 kHz.

8. Equipment at the transmitting sites

The right hand section of Fig. 2 shows the arrangement of the transmitter and its drive equipment at Westerglen. The arrangement at Burghead is identical.

The phase adjustment of the transmitter is made by a digital phase shifter operating at 5 MHz and placed between the frequency standard and the 5 MHz to 200 kHz divider. The phase shifter is operated by a control unit which is connected to the monitoring site via the tone signalling equipment described in the previous section.

Failure of the digital phase shifter, its control unit or its power supply could cause a break in transmission, and so the whole system is duplicated with the reserve drive being fed from a crystal oscillator (see Fig. 2). It is unlikely that the frequency of the crystal oscillator will be accurate enough for the system to maintain lock (see Section 4). However, this arrangement does have the advantage that if a spare rubidium standard becomes available it can easily replace the crystal oscillator.

8.1. Control unit

The demodulated tones are passed from the line signalling equipment to the phase shifter control unit where they are decoded back to the original instructions sent from the monitoring site. Every 8 seconds the control circuit looks at the instructions and if a change is required it operates the 5 MHz phase shifter. If an advance or retard signal has been sent it causes the 5 MHz phase shifter to advance or retard one increment in phase (an increment is about 33° at 5 MHz). If a fast advance or retard is asked for it moves the phase shifter 16 increments.

The controller will only operate the phase shifter once every 8 seconds for two main reasons. Firstly, it is necessary to allow a second or so after a phase change for the phase locked loops in the receivers to settle. Secondly, to ensure that a fast signal is being sent, it is necessary to look at the lines for about 2 seconds before being certain that a 2.5 Hz square wave is present. Therefore, it is necessary to wait about 3 secs before making another change. In fact, the system is operated every 8 secs to provide a margin of stability, bearing in mind the use of two systems in tandem.

8.2. The digital phase shifter

The phase shifter operates on the 5 MHz signal obtained directly from the rubidium frequency standard; a block diagram of it is shown in Fig. 12. The heart of the circuit is the variable divider shown in the left of the diagram. Normally this would divide the incoming 5 MHz by 10 to produce a 500 kHz output. If a phase advance is required the circuit is made, in effect, to divide by 9 for 1 cycle of the output; to retard it is made to divide by 11 for 1 cycle. This means that the output signal from the divider can be either advanced or retarded by 1/10 of a cycle i.e. 36° in phase. The 500 kHz output from the divider is mixed with the incoming 5 MHz and the resulting 5.5 MHz filtered out. The 5.5 MHz signal is still variable in ±36° steps. Finally, a 10/11 divider brings the output frequency back to 5 MHz and consequently the phase steps are also divided by 10/11 i.e. ±32.7 at 5 MHz.

As this phase shifter has no end stop it can compensate for a small frequency error in the input signal by continuously phase shifting in one direction.

The output of the phase shifter is divided by 25 to 200 kHz to provide the drive frequency for the transmitter. The phase steps are also divided by 25 to give steps of ±1.3° at 200 kHz. When a fast advance or fast retard is required the phase shifter is made to do 16 steps at a rate

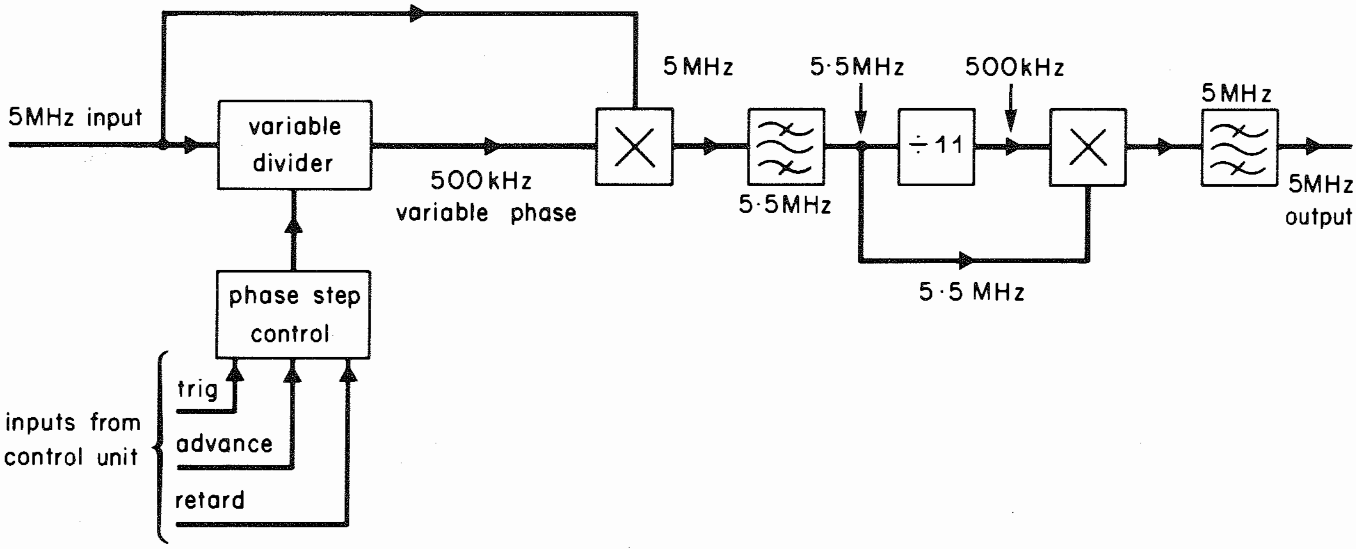

Fig. 12 - 5 MHz digital phase shifter

of about 1 step every 2 ms, the total phase shift is then 21° at 200 kHz.

8.3. Pull-in time of the phase locking system

If a sudden change of phase is introduced into one of the transmitter drives then the system will operate to correct the phase, and it will make phase adjustments every 8 seconds until the phase is corrected within ±3°. The longest pull will occur if a 180° phase change has been introduced. Initially, the phase will be corrected on either fast-retard or fast-advance in 21° steps (i.e. 159°, 138° etc.) down to 12° when the system will start to move in steps of 1.3° until it gets to a phase error of 2.2° when it will stop. It will have taken 8 fast steps and 6 slow steps, so the total time taken will be 112 seconds. If the phase change occurred 8 seconds before the start of correction, the total time would then be 2 minutes, which is the longest possible time it should take to achieve the correct phase.

9. The performance of the phase locking system

The performance of the system has been examined in two ways. First, chart recorders were installed at the two transmitters in order to record the control signals over a period of time. Second, the standing wave pattern was observed on the ground and shown to be controlled by the monitoring station.

Fig. 13 shows the record for a winters day at Westerglen. During the middle of the day (region A in Fig. 13) there are only occasional corrections and these are equally likely to be

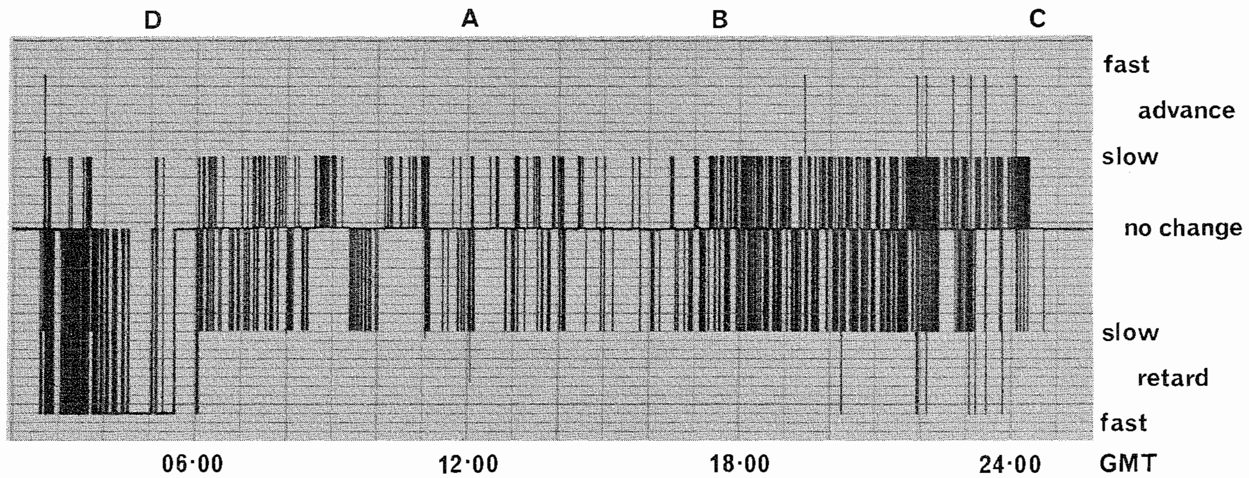

Fig. 13 - Record of control signals received at Westerglen, 24th February, 1979

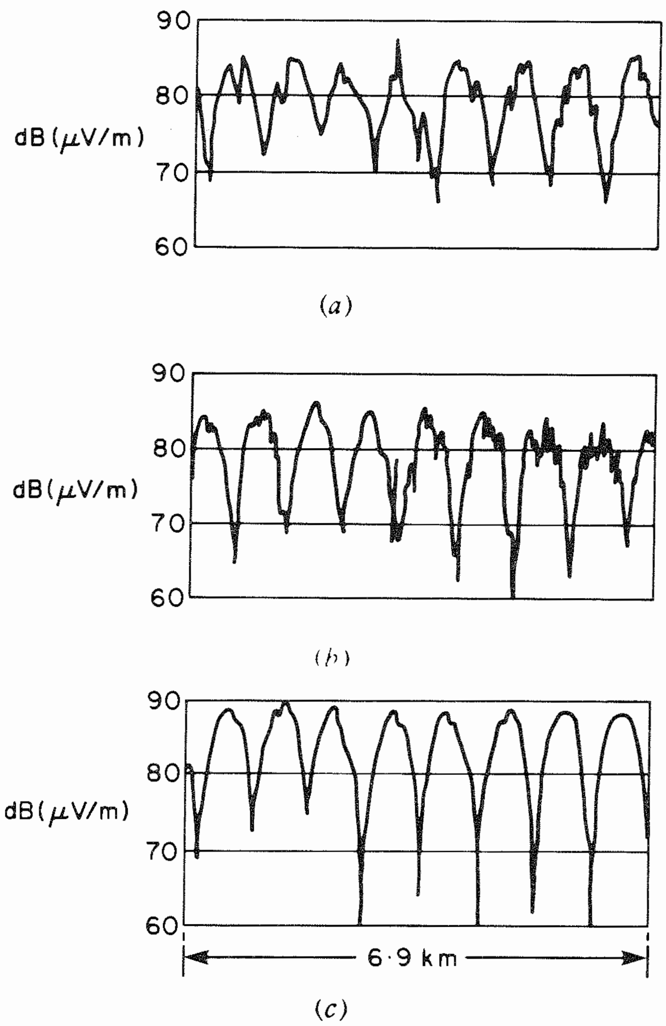

Fig. 14 - Measured standing-wave patterns for different conditions:
(a) E-field, normal (b) E-field shifted 180° (c) H-field shifted 180°

advances as retards, indicating a close adjustment of the two transmitter frequencies. Around sunset (B) the number of corrections increases and includes some fast steps. These cease abruptly at C as both transmitters are switched off and the controls become frozen. In the early morning, at D, one only of the transmitters (Droitwich) is switched on and is evidently able to lock both receivers since a period of fast retards is found. These, however, are not implemented because the transmitter being controlled (Westerglen) is not operational at the time.

The standing wave pattern produced in the zones where the field strengths from Droitwich and Westerglen were nearly equal was surveyed in some detail. Fig. 14 shows some surveys of a section of the A68 road in Northumberland; this section was straight and in a direction almost normal to the standing-wave pattern. The surveys were made using a RC1M/21 measuring receiver and chart recorder fitted in a car. In Fig. 14(*a*) the measurement is of the E-component of field using a vertical whip aerial. A 180° phase change was then inserted at Pontop Pike by means of the phase adjuster unit and the measurement repeated. The result is shown in Fig. 14(*b*) where the pattern is seen to be moved by 180°. Finally the H-component of the field was measured using a crossed-loop aerial (the 25 Hz switching facility of the RC1M/21 receiver was not used for this measurement). The result is seen in Fig. 14(*c*). The H-field has its maxima interleaved with those of the E field and they are higher and less subject to local disturbance.

It may be seen from Fig. 14 that the zones where the field is less than, say, +70 dB(μV/m) or 3 mV/m are very small. The quality of reception in these minima is governed by a number of factors, one of the more important being modulation delay equaliszation to be considered in the next section. Given the idealized conditions of a deep minimum and little other noise, it may be possible to hear the large phase increments as occasional short bursts of low-level buzz. In practice these are likely to be inaudible wherever the signal is of a good enough quality for listening. It may also be noted from Fig. 14 that there is everywhere an acceptable component of field, either E or H, although relatively few domestic listeners are likely to have a receiver capable of making use of this fact. Motorists must accept a drop-out as their vehicle passes through a minimum. Such drop-outs, however, are not unduly disturbing.

Fig. 15 shows part of the standing-wave pattern, deduced from observations with a whip aerial, in Redesdale, Northumberland.

10. Modulation delay equalization

As part of the project, it was required to minimize distortion in the minima of the standing-wave pattern by equalizing modulation delay. This involved measuring and correcting dispersion on the circuits to each transmitter and inserting suitable fixed delays so that the modulation arriving at a prescribed point from adjacent transmitters would be in phase at all modulation frequencies. It also meant providing equipment for checking that there were no inadvertant phase reversals on the modulation circuits. The detailed description of these measurements and of the equipment design, which were undertaken by Communications Department and Designs Department, is beyond the scope of this report. The

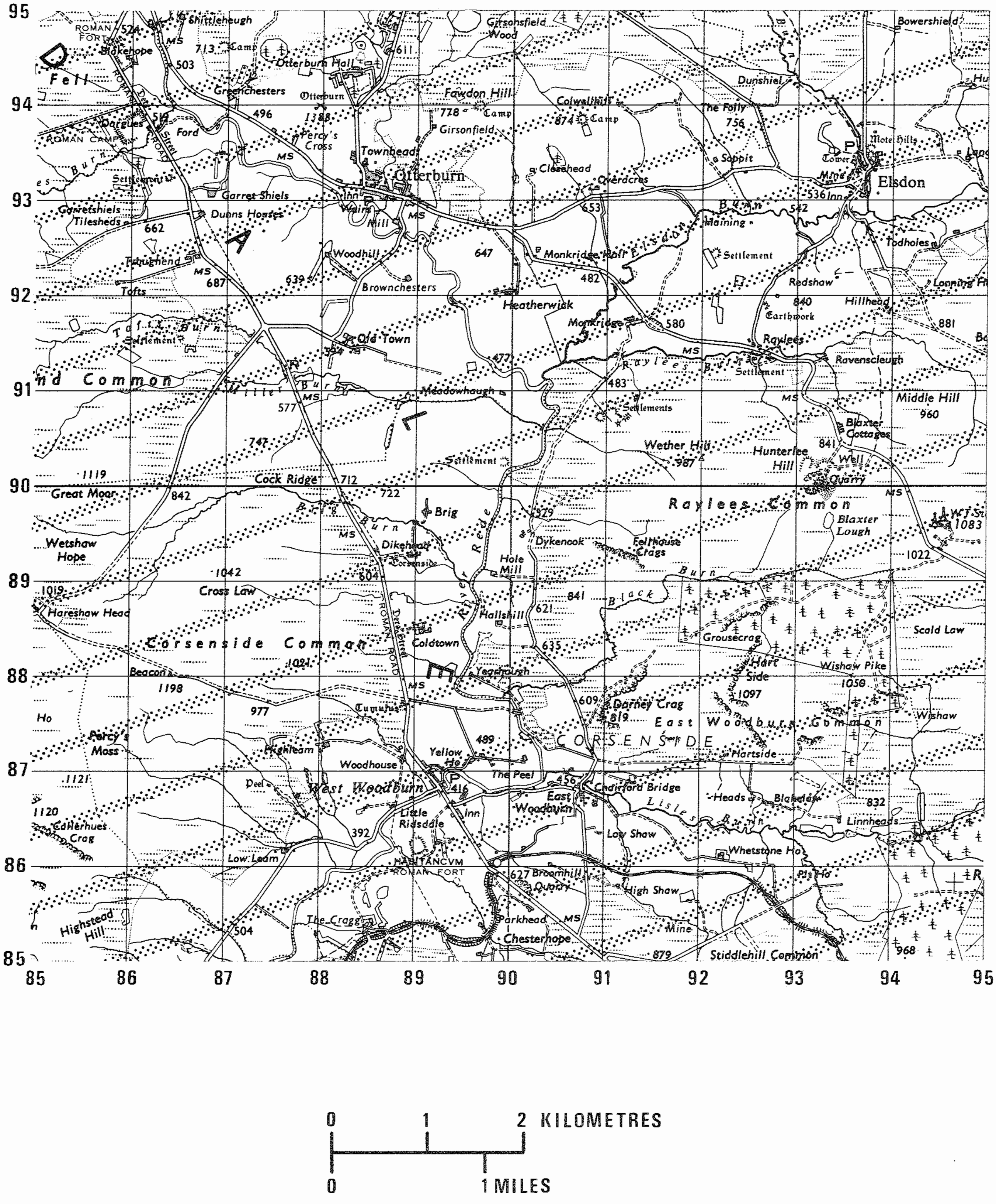

Fig. 15 - Occurrence of standing-wave patterns in Redesdale, Northumberland

(RA-186)

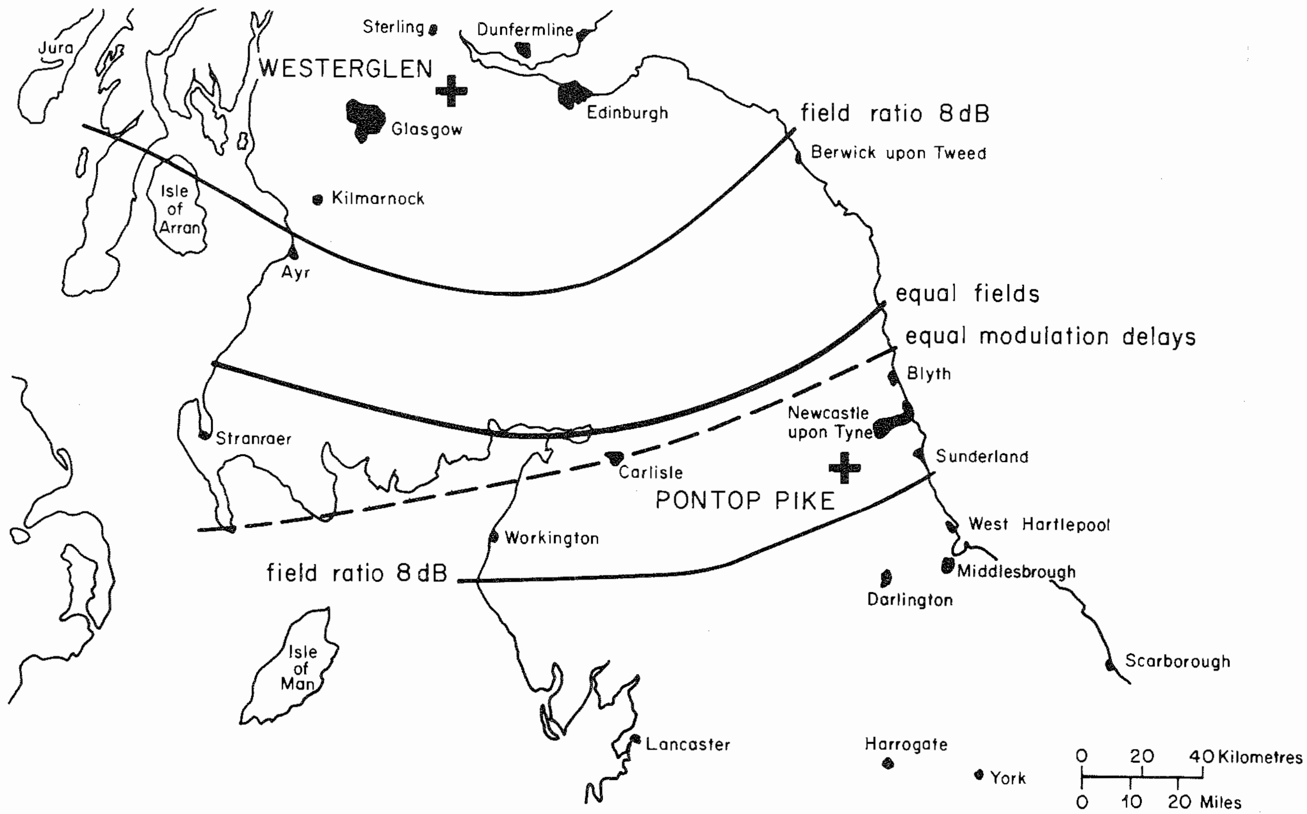

Fig. 16 - Loci of constant field strength ratio and equal modulation delays: Droitwich-Westerglen

specification of the delays is, however, relevant.

In the case of the Droitwich-Westerglen overlap, the line of equal field strengths was expected to pass to the north of Stranraer, over south west Scotland and just to the north of Carlisle to Amble on the Northumberland coast. Newcastle-upon-Tyne and Carlisle are provided with low-power transmitters carrying the Radio-4 (UK) service. Scotland has an additional service (Radio Scotland) from a high-power transmitter at Westerglen supported by a low-power one at Dumfries. For this reason it was required to give a small bias in favour of the service in England by making the modulation delays equal on a line slightly to the south of the equal-field-strength line. Fig. 16 shows the positions of the two lines. The corresponding values of relative delay at Pontop Pike (a convenient measuring point) is for modulation on the Droitwich signal to lead that on the Westerglen signal by 175 μs.

In the case of the Westerglen-Burghead overlap, Aberdeen is provided with a low-power transmitter carrying the Radio-4 (UK) service. The line of equal field strength passes through Spean Bridge in the west and Inverbervie in the east, the greater part of its run being through uninhabited country. The best arrangement would seem to be to optimize for Inverbervie and the littoral plain. Fig. 17 shows the relative positions of the two lines. The corresponding value of relative delay at Aberdeen (a convenient measuring point) is for modulation on the Burghead signal to lead that on the Westerglen signal by 175 μs.

11. Conclusions

The work described above was started in March 1978. The equipment was designed, constructed, tested and installed ready for service operation by November 23rd, 1978. In view of such a short time scale it would be hardly surprising if some features of the original designs needed modification in the light of experience. In fact, the only aspect needing significant improvement is that of the design of directional receiving aerials. The problem is that of getting sufficient directivity from aerials within the confines of a site that is small in wavelengths. The problem is still under study and some improvement is expected. The problem was exacerbated by a prolonged period of low-power operation at Westerglen. Nevertheless, the system has functioned satisfactorily for all but a small fraction of the time. A survey of the overlap zone on the

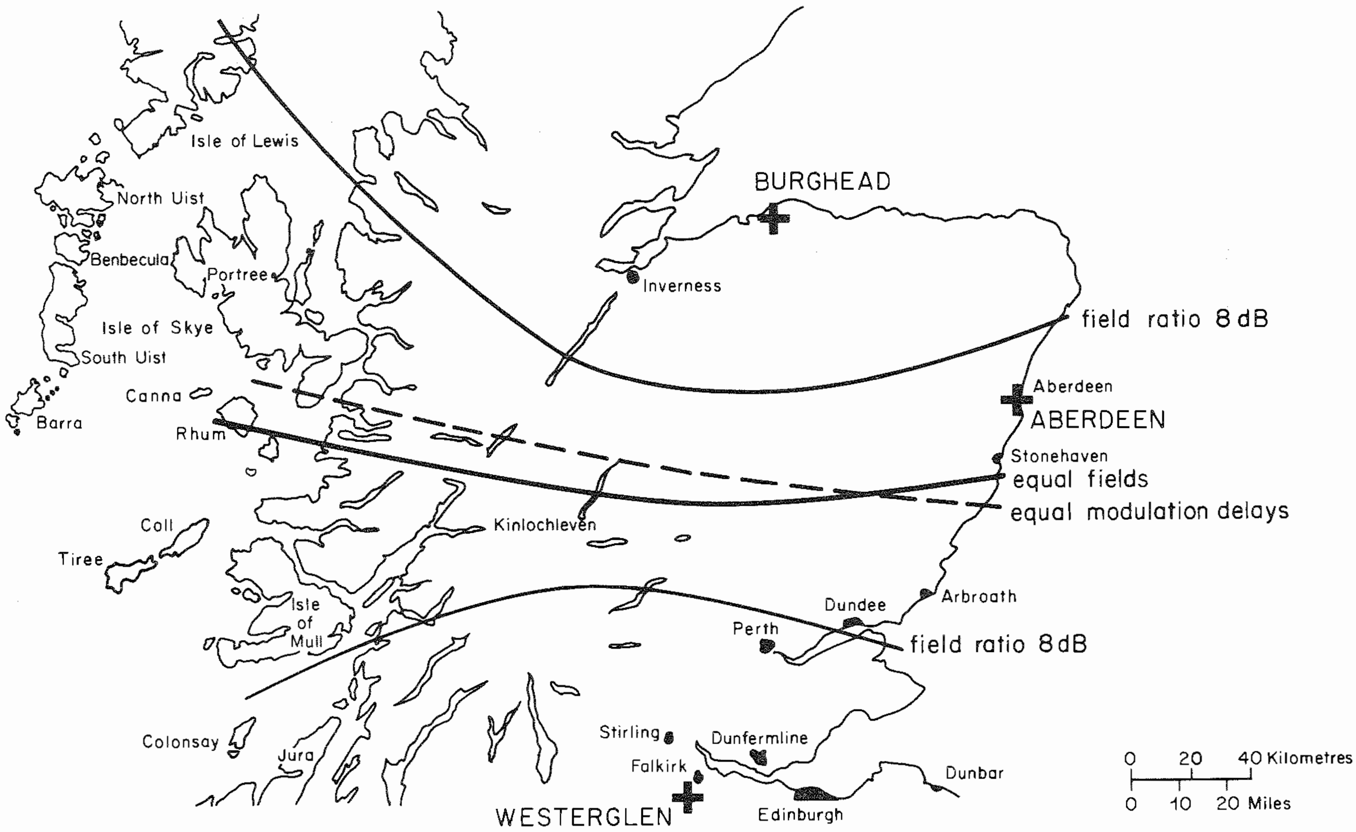

Fig. 17 - Loci of constant field strength ratio and equal modulation delays: Westerglen-Burghead

English/Scottish border has demonstrated the effectiveness of the phase control and has shown that very few listeners will be affected by the residual distortion.

The listener who is still affected by distortion has two possible means of minimizing it. First, if he has a directional receiving aerial (e.g. a ferrite) he may rotate it to increase the amplitude ratio of the two carriers provided that he is not located on the line joining the transmitters. Second, if reception is still poor using a ferrite, which responds to the H-component of the field, an improvement may be obtained by connecting an external whip or open wire aerial which responds to the E-component of the field. Neither approach is of use to the motorist travelling through the standing-wave pattern.

It is of interest to consider the Radio-4 (UK) network in terms of the efficiency of spectrum usage. Consider first an idealized lattice of transmitters all having the same power and sharing the same frequency channel. If all the transmitters carry different programmes it is necessary to space them apart by distances very much greater than the individual service radius. The area receiving a service expressed as a proportion of the total area is quite small; typical figures for a m.f. and l.f. service by night would be 0.5% and 2% respectively. (If consideration were restricted to day time, these figures would be somewhat greater.) A great improvement in coverage efficiency may be made by radiating the same programme from each transmitter, since the distance between adjacent transmitters may be less for the same degree of interference. Thus the Radio 3 network on 1215 kHz has been estimated to have an area coverage efficiency of 46% by day. It may now be seen that the synchronization of the Radio-4 (UK) network transmitters together with delay equalization is a further step along the same path, increasing the day-time coverage efficiency to 95% or more. The possibility of obtaining some improvements to the Radio-2 and Radio-3 networks by carrier synchronizing is under consideration.

12. Acknowledgements

In view of the very short time scale available for the work, use was made of existing BBC Designs Department equipment wherever possible. Reference is made in the text to the use of the ferrite receiving aerials and to the line signalling equipments. In addition, the design of the 5 MHz digital phase shifter was derived in part from that

of the UN17/529 digital phase shifter for colour sub-carrier in the Natlock system. Similarly, the design of the phase comparator stemmed in part from that of the m.f. carrier meter ME6/2.

Assistance in installing and setting up the equipment was given by the BBC Communications and Transmitter Capital Projects Departments and by Transmitter Group.

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Appendix I

The effect of imperfect receiving aerial directivity

Let the master signal produce at the input to the phase comparator on the monitoring site a signal

$$a \sin \omega t$$

Similarly let the slave station produce a signal

$$b \sin \overline{\omega t + \phi}$$

It is required to measure the phase difference ϕ.

Suppose that the aerial receiving the master signal also receives a fraction p of the slave signal so that its output is

$$a \sin \omega t + p\, b \sin \overline{\omega t + \phi}$$

Suppose also that the aerial receiving the slave signal also receives a fraction q of the master signal so that its output is

$$b \sin \overline{\omega t + \phi} + q\, a \sin \omega t$$

Since the frequencies of these two signals are the same, the time dependent terms may be omitted. The measured phase difference, ϕ', between the signals from the two aerials is then

$$\phi' = \tan^{-1} \frac{b \sin \phi}{qa + b \cos \phi} - \tan^{-1} \frac{pb \sin \phi}{a + p\, b \cos \phi}$$

In normal operation ϕ and ϕ' may be assumed to be small near balance so that

$$\phi' \approx \frac{b\phi}{qa + b} - \frac{pb\phi}{a + pb} \qquad \text{(I)}$$

By way of example, assume equal fields at the monitoring site ($a = b$) and let the receiving aerials each have a directivity of 20 dB ($p = q = 0.1$). Then

$$\phi' \approx \frac{\phi}{1.1} - \frac{0.1\phi}{1.1}$$

$$\approx 0.82\phi$$

i.e. the measured phase is 18% less than the actual phase.

Now at Pontop Pike during low-power operation at Westerglen, the field of the latter was 9 dB less than that of Droitwich, i.e.

$$a = 1 \qquad b = 0.35$$

Then with aerial directivities of 20 dB ($p = q = 0.1$)

$$\phi' \approx \frac{0.35\phi}{0.45} - \frac{0.035\phi}{1.035}$$

$$\approx 0.74\phi$$

and the measurement is 26% low.

Appendix II

The effect of a third transmitter

For simplicity, assume that the receiving aerials have high directivity so that the signal picked up from the unwanted member of a pair of adjacent transmitters may be neglected. The signal reaching the phase comparator from the aerial receiving the master station is then

$$a\underline{/0}$$

and that from the aerial receiving the slave station is

$$b\underline{/\phi}$$

Now consider a third synchronised transmitter which induces signals $C_a\underline{/\psi_a}$ and $C_b\underline{/\psi_b}$ in the master and slave receiving aerials respectively. The composite signal from the master receiving aerial is then

$$a\underline{/0} + C_a\underline{/\psi_a}$$

$$= a + C_a \cos \psi_a + \mathrm{j}\, C_a \sin \psi_a$$

Similarly the signal from the slave receiving aerial is

$$b\underline{/\phi} + C_b\underline{/\psi_b}$$

$$= b \cos \phi + \mathrm{j}\, b \sin \phi + C_b \cos \psi_b + \mathrm{j}C_b \sin \psi_b$$

The phase angle, ϕ', between these two signals, as measured by the monitoring system, is

$$\phi' = \tan^{-1} \frac{b \sin \phi + C_b \sin \psi_b}{b \cos \phi + C_b \cos \psi_b}$$

$$- \tan^{-1} \frac{C_a \sin \psi_a}{a + C_a \cos \psi_a}$$

For closely-spaced receiving aerials, ψ_a, ψ_b will be nearly equal but will have arbitrary values. Put $\psi_a = \psi_b = \psi$ and consider for $\psi = 0, 90°, 180°$.

(i) For $\psi = 0$ $\quad \phi' = \tan^{-1} \dfrac{b \sin \phi}{b \cos \phi + C_b}$

$$\approx \frac{b\phi}{b + C_b} \qquad \text{near balance}$$

Putting in the appropriate numerical values of ground wave we find for Pontop Pike

$$\phi' = 0.83\phi$$

and for Aberdeen

$$\phi' = 0.86\phi$$

(ii) For $\psi = 90°$

$$\phi' = \tan^{-1} \frac{b \sin \phi + C_b}{b \cos \phi} - \tan^{-1} \frac{C_a}{a}$$

$$\approx \tan^{-1} \frac{b\phi + C_b}{b} - \tan^{-1} \frac{C_a}{a} \quad \text{near balance}$$

For Pontop Pike we find

for $\phi = 0$, $\quad \phi' = 11.3°$

and for Aberdeen

for $\phi = 0$, $\quad \phi' = 8.8°$

(iii) For $\psi = 180°$

This case is similar to $\psi = 0$ and we find

for Pontop Pike $\quad \phi' = 1.25\phi$

and for Aberdeen $\quad \phi' = 1.19\phi$

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Printed by BBC RESEARCH DEPARTMENT, Kingswood Warren, Tadworth, Surrey, KT20 6NP